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THESIS

A FIELD STUDY OF OCEANIC
TURBULENT HORIZONTAL DIFFUSION

by

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June 1968

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OCEANIC TURBULENT HORIZONTAL DIFFUSION

by

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ABSTRACT

Richardson's "four-thirds law" of horizontal diffusion was tested using aerial photography as a data gathering technique. Plywood floats and current crosses suspended both near the surface and at nine feet were used as diffusers. The scales investigated ranged from 10 to 525 meters. The investigation was conducted in 36 fathoms of water, 3000 meters from the nearest land in Monterey Bay, California. Stommel's (1949) method of analysis was used.

The results indicate a clear dependence of diffusion on diffuser weight and lend some evidence to Robert's (1961) theory of turbulent diffusion, in that the diffusion increases more rapidly with scale than proposed by Richardson (1926). This conclusion is supported by the use of confidence limits upon the data.

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1. Horizontal Turbulent Diffusion and Richardson's "Four-Thirds Law"

Oceanic diffusion is not well understood and a difficult process to describe mathematically. The one-dimensional Fickian law of diffusion is

$$\frac{\partial \nu}{\partial t} = K \frac{\partial^2 \nu}{\partial \chi^2}$$

where ν is the concentration of a substance, χ is position, t is time and K is the diffusivity (a measure of the rate of diffusion) of the substance. This equation adequately describes molecular diffusion, which is dominated by concentration gradients. Using the Fickian equation, Stommel (1949) pointed out that the probability of two discrete particles initially a distance b_o apart being a distance b_1 apart at a time t later would be

$$P(b_0, b_1) = \frac{1}{2\sqrt{\pi K t}} \exp\left[-\frac{(b_1 - b_0)^2}{4Kt}\right].$$

In effect this equation states that the probability of the diffusing particles' change in separation with time is a function of $(b_o - b_1)^2$ only, and not b_o or b_1. This result is not supported by experimental data.

Richardson (1926), on the basis of six atmospheric diffusion experiments having length scales of from 1.5 x 10^3cm. to 5 x 10^6 cm., postulated a new equation to describe diffusion in a turbulent medium. He noted that the basic difference between molecular diffusion and turbulent diffusion was that the independent variable for the latter was the particle's separation from its neighbors and not the particle's position, and proposed the equation

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial \ell}\left[F(\ell)\frac{\partial q}{\partial \ell}\right].$$

Here, ℓ is the distance between the particles and is called the "neighbor separation." The number of particles having neighbors with neighbor separations between ℓ and $\ell + d\ell$ is given by $q(\ell)d\ell$ where $q(\ell)$ is the "neighbor concentration." The neighbor concentration can also be regarded as the probability that two particles will be a distance ℓ apart. The term $F(\ell)$ is the "neighbor diffusivity" and is analogous to the diffusivity in the Fickian equation.

Atmospheric experimental data and mathematical simplicity led Richardson to suggest that $F(\ell)$ has the form

$$F(\ell) = K\,\ell^{4/3}$$

where K is an empirically derived constant. This is commonly referred to as the "four-thirds law." Stommel (1949), on the basis of data obtained using aerial photography, suggested that the four-thirds law was also applicable to oceanic turbulent diffusion. If it is assumed that the physical governing quantities are ℓ and ϵ (the turbulent energy dissipation per unit mass) dimensional analysis shows that $F = c\,\ell^{4/3}\epsilon^{1/3}$, where c is dimensionless. Thus $K = c\,\epsilon^{1/3}$, so that K will vary with the turbulent energy dissipation, or probably the turbulent energy itself. This is certainly reasonable and leads one to expect a variety of values of K.

2. The Standard Method of Determining Neighbor Diffusivity as a Function of Neighbor Separation

The commonly accepted method of determining oceanic neighborhood diffusivity as a function of neighbor separation is by means of pairs of floats released simultaneously on the water surface. Let l_0 be the separation of a pair of floats at time t_o and l_1 the separation at a later time t_1. The interval of time $t_1 - t_o$ is chosen so that the ratio $(l_1 - l_0)/l_0$ is of the order of 1/10. The time interval is then a function of the scale, l_0. Richardson's equation may then be written as

$$\frac{\partial q}{\partial t} = F(l_0)\frac{\partial^2 q}{\partial l^2}.$$

which has the solution

$$q(l_1) = \frac{\text{CONST.}}{\sqrt{t}} \exp\left[-\frac{(l_1 - l_0)^2}{4tF(l_0)}\right].$$

Thus the neighbor separation has a Gaussian distribution. The standard deviation of l_1 from the mean l_0 is $\sqrt{2tF(l_0)}$ so that the neighbor diffusivity for the value l_0 is

$$F(l_0) = \frac{\overline{(l_1 - l_0)^2}}{2t}$$

where the bar denotes the mean of many pairs. Since all pairs will not have the same initial separation l_0, a mean value of l is used: $F\left(\frac{l_0 + l_1}{2}\right) = \frac{\overline{(l_1 - l_0)^2}}{2t}$.

Many individual studies have been conducted to test Richardson's four-thirds law. These are listed in the references. While general agreement exists as to the validity of the four-thirds law, the data has never been sufficient to actually confirm the law, and a value of the constant C has not been determined. Rather, a range of values of K can be found in the literature, from 0.006 to 0.09 $cm^{2/3}sec^{-1}$. These values have usually been found by passing a best-fit line of 4/3 slope through the data points plotted on a log-log scale. Little attention has been paid to the slope itself, or to random sampling errors and resulting confidence limits on both the slope and the constant K. This should be corrected, especially as recent developments in turbulence theory (Roberts, 1961) predict that the slope should be 3/2 instead of 4/3. This field study is a first step in that direction.

3. Objectives of the Field Study

The field study has two main objectives. First, to investigate Richardson's four-thirds law using as many observations as practical. Second, to further investigate subsurface horizontal diffusion as was first done by Snyder (1967), who found a marked change in diffusivity with depth. The greatest possible scale commensurate with technique and available equipment was studied. Measurements of scales ranging from 10 to 525 meters were obtained.

4. Techniques Employed to Obtain Diffusion Data

A T-11 Fairchild aircraft mapping camera was obtained from the Naval Oceanographic Office, Suitland, Maryland. This camera uses a 6-inch f:6.3 (Bausch and Lomb) class T metrogon lens to obtain 9-1/2 x 10-1/4 inch negatives from a film supply roll with a 390 foot capacity. This length of film is sufficient for between 450 and 460 negatives. The operation of the camera is completely automatic and is driven by a 27.5 volt d.c. motor which derives its power from the aircraft's main electrical system. A vacuum of 2" mercury is used to hold the film flush against the focal-plane frame. The inner edges of this focal-plane frame form a 9 x 9 inch perimeter for a picture area on each film negative. Other features incorporated in the T-11 camera (which make it ideally suited for diffusion studies) are an altimeter, a navigational clock, a data recorder and a built-in filter with a 1.5 index. Time, altitude and other pertinent information such as date of flight were thus recorded on the margin of each negative. The sweep second hand allowed time to be read to within 0.01 seconds. Comparison of the aircraft and the camera altimeters showed them to agree perfectly. The camera was mounted in a Navy US2-A aircraft in such a manner that level flight ensured the axis of the camera to be in the vertical. From the aircraft's flight instruments it was ascertained that all picture-taking runs were within two degrees of level flight. Operating under these conditions ensured a linear length scale over each negative for easy measurement.

The diffusing particles consisted of 2' x 4' x 1/4" plywood floats, weighing about 10 pounds. To each float was attached a metal current cross consisting of four mutually perpendicular vanes, 6 inches wide and 35 inches long. The current crosses weighed nine pounds, and required additional buoyancy to remain afloat. Styrofoam sheets were used for this purpose and an almost neutral buoyancy was achieved. This minimized any direct effect of the wind on the floats.

In the first three runs half the floats had current crosses at nine feet; the remaining floats had current crosses just beneath the surface. All floats were painted white. A 10-inch red stripe was painted diagonally across the floats whose current crosses were near the surface. These red stripes were easily recognizable on the negatives. A total of twenty-three floats was used.

Data were taken on March 21, 28, April 4 and April 18, 1968. The final run made used seventy-four floats without current crosses. A 40-foot motor launch set out the diffusers on the first two runs and a 63-foot converted torpedo retriever on the last two runs.

The floats were put out in pairs; the individual floats composing each pair were 30 feet apart. On the first three runs each pair consisted of a float with a current cross at nine feet and one with a current cross near the surface. The initial pattern was laid out in a circle with an approximate diameter of 300 feet. The diameter of the initial pattern on the fourth run was 450 feet due to the large number of floats used. After laying the pattern the boat stayed as near to the center of the pattern as was possible without causing propeller wash (which could have a definite harmful effect on the study).

The experiment was conducted in Monterey Bay, California, in approximately 36 fathoms of water and about 3,000 meters from the nearest point of land. The exact initial position each time was 36°38.6' north latitude, 123°53.3' west longitude.

The pictures were taken at intervals of between three and four minutes at altitudes of 1,000 feet for the first three runs and 2,000 feet on the fourth run. Wind conditions were taken as those reported by Monterey Municipal Airport, and are shown in Table I below.

TABLE I

Wind Data

Run	Date	Wind Direction	Wind Velocity
1	3-21-68	100° - 140°	5.0 m/sec
2	3-28-68	250° - 280°	2.5 - 4.0 m/sec
3	4-04-68	320° - 340°	1.5 - 3.1 m/sec
4	4-18-68	300° - 320°	2.5 - 5.0 m/sec

During the second run a swell of four to six feet from the west (the same direction as the wind) was reported by the motor launch. No significant wave or swell activity was encountered on runs one and four. Some breaking waves were noticed from the air during the early stages of run three, but these subsided before the run was completed. The sighting of whitecaps and the report from the motor launch of actual sea conditions was not commensurate with the reported wind, which is therefore suspected to be in error.

5. Data Analysis

A series of one to three pictures at three-second intervals was taken on each pass of the aircraft over the diffusing particles. Without the use of optical photo-navigational equipment, and using only the motor launch as a reference system, it was very difficult to fly directly over the center of the diffusing particles. As a consequence some floats did not appear in all pictures and were therefore eliminated from further analysis. Table II contains the pertinent information for each of the four runs.

TABLE II

Run 1 (23 floats)

Altitude 1 (feet)	Altitude 2 (feet)	Delta t (min)	Pass
1,000	1,180	4.09	1&2
1,180	1,120	4.14	2&3
1,120	1,060	3.73	3&4
1,060	1,160	4.10	4&5
1,160	1,060	3.92	5&6
1,060	1,020	4.44	6&7
1,020	1,080	3.51	7&8
1,080	1,040	4.50	8&9
1,040	1,000	4.36	9&10
1,000	1,040	4.31	10&11
1,040	1,060	4.39	11&12
1,060	1,000	4.40	12&13
1,000	1,060	3.15	13&14

Run 2 (14 floats)

1,100	980	3.53	1&2
980	1,020	3.92	2&3
1,020	1,020	11.30	6&7

TABLE II (cont.)

Altitude 1 (feet)	Altitude 2 (feet)	Delta t (min)	Pass
1,020	1,080	3.63	7&8
1,080	1,000	3.67	8&9
1,000	1,000	3.87	9&10
1,000	980	4.20	10&11
980	960	3.90	11&12
960	960	3.85	12&13

NOTE: Passes 4 & 5 were not used because less than half the floats appeared in each of the negatives.

Run 3 (21 floats)

1,060	1,080	4.18	1&2
1,080	1,100	4.49	2&3
1,100	1,040	4.36	3&4
1,040	1,080	4.10	4&5
1,080	1,080	8.54	7&8
1,080	1,040	8.00	10&11
1,040	1,000	4.33	11&12

NOTE: Passes 6 & 9 were not used because less than half the floats appeared in each of the negatives.

Run 4 (44 floats)

2,040	2,000	3.10	1&2
2,000	1,980	3.37	2&3
1,980	2,000	3.30	3&4

A transparency was made for each negative, and was used with a Travel-Graph overhead projector. An enlargement factor of five was obtained when the transparencies were projected on a plain white paper sheet stretched and taped to a wall. A simple color coding scheme was used to mark each float on the paper sheet. Each pass of a run was represented by its own symbol and each float was further identified as to vertical location of the current cross. In this manner the position of each float was tracked throughout the duration of the run. The paper sheet was placed on a cork bulletin board and a colored pin placed in the center of each mark representing the position of a float. A different color pin was used for each pass. This simple scheme allowed for positive identification of each float. The ranges and bearings of the floats were then measured from a convenient reference point near the center of the pattern. This reference point could vary from pass to pass. Ranges were measured to within 0.025 inches and bearings to within 0.25 degrees. A digital computer was used to calculate initial distance ℓ_0, changes in distance $\ell_1 - \ell_0$, mean distance $\frac{1}{2}(\ell_0 + \ell_1)$, and neighborhood diffusivity $\frac{(\ell_1 - \ell_0)^2}{2t}$ for each neighbor pair. Ranges measured in inches were converted to the proper scale in meters using the relationship;

$$\frac{\text{IMAGE}}{\text{FOCAL LENGTH}} = \frac{\text{GROUND COVERED}}{\text{ALTITUDE}} \quad .$$

Histograms were drawn for each run and values of $\frac{1}{2}(\ell_0 + \ell_1)$ were separated into class intervals. The sizes of the class intervals were selected in such a manner that each group had about the same number of values. The values of F in each class were then averaged to obtain the $\bar{F}$ for that class interval.

6. Results and Conclusions

A total of 2,374 observations covering scales of 10 to 525 meters were made. The results are given in Tables III - V.

TABLE III

(current crosses near surface)

Run 1

Class Interval (meters)	Number of Values Avg.	$\tilde{\ell}$ (meters)	$\overline{F(\ell)}$ (meters^{2}sec^{-1})
10 - 61	47	37.8	0.0104
61 - 79	46	70.6	0.0392
79 - 98	44	91.2	0.0628
98 - 112	43	111.0	0.0500
112 - 146	42	132.0	0.1255
146 - 170	61	158.0	0.1619
170 - 198	45	182.0	0.1785

Run 2

Class Interval (meters)	Number of Values Avg.	$\tilde{\ell}$ (meters)	$\overline{F(\ell)}$ (meters^{2}sec^{-1})
10 - 61	18	36.0	0.0096
61 - 92	21	76.4	0.0215
92 - 107	23	98.2	0.0602
107 - 122	23	114.0	0.0884
122 - 174	27	142.0	0.1040

TABLE III (cont.)

Run 3

Class Interval (meters)	Number of Values Avg.	$\bar{\ell}$ (meters)	$\overline{F(\ell)}$ (meters^{2}sec^{-1})
10 - 122	30	65.5	0.0271
122 - 153	25	131.0	0.1160
153 - 183	21	164.0	0.0854
183 - 200	25	193.0	0.1250
200 - 228	25	213.0	0.2110
228 - 258	27	236.0	0.1490
258 - 305	20	281.0	0.1710
305 - 352	22	339.0	0.4140

TABLE IV

(current crosses at nine feet)

Run 1

Class Interval (meters)	Number of Values Avg.	$\bar{\ell}$ (meters)	$\overline{F(\ell)}$ (meters^{2}sec^{-1})
10 - 61	53	40.7	0.0130
61 - 79	49	70.5	0.0393
79 - 98	47	88.8	0.0464
98 - 116	48	105.2	0.0778
116 - 134	52	126.3	0.1096
134 - 153	57	141.9	0.1374
153 - 211	78	174.4	0.2584

Run 2

Class Interval (meters)	Number of Values Avg.	$\bar{\ell}$ (meters)	$\overline{F(\ell)}$ (meters^{2}sec^{-1})
21 - 61	25	43.4	0.0146
61 - 92	33	77.6	0.0510
92 - 107	23	98.7	0.0959
107 - 137	25	117.0	0.0685
137 - 256	25	184.0	0.1923

Run 3

Class Interval (meters)	Number of Values Avg.	$\bar{\ell}$ (meters)	$\overline{F(\ell)}$ (meters^{2}sec^{-1})
10 - 107	42	76.2	0.0356
107 - 152	39	129.0	0.0750
152 - 183	48	166.0	0.0948
183 - 228	47	207.0	0.1450
228 - 276	35	247.0	0.3460
276 - 350	45	315.0	0.5060

TABLE V

(no current crosses)

Run 4

Class Interval (meters)	Number of Values Avg.	$\overline{\ell}$ (meters)	$\overline{F(\ell)}$ (meters^{2}sec^{-1})
10 - 91	101	53.6	0.0226
91 - 152	85	124.5	0.1078
152 - 212	101	183.5	0.2945
212 - 290	115	254.0	0.4475
290 - 320	107	308.0	0.6570
320 - 348	106	334.0	0.7760
348 - 385	122	364.0	0.8560
385 - 425	117	402.0	0.9248
425 - 525	114	452.0	1.0780

The results were also plotted on logarithmic paper, as neighbor separation $\overline{\ell}$ versus neighbor diffusivity $\overline{F(\ell)}$ (Figures 1-3). The values of K varied little from run to run even though whitecaps were present on one of the runs and wave and swell conditions varied from run to run. Table VI gives the values of K for visually estimated best-fit lines of four-thirds slope and compares these values with those of Ozmidov (1957) and Snyder (1967). These values are accurate to only one significant figure owing mainly to sampling errors associated with confidence limits discussed below.

TABLE VI

(values of K in cm.$^{2/3}$sec^{-1})

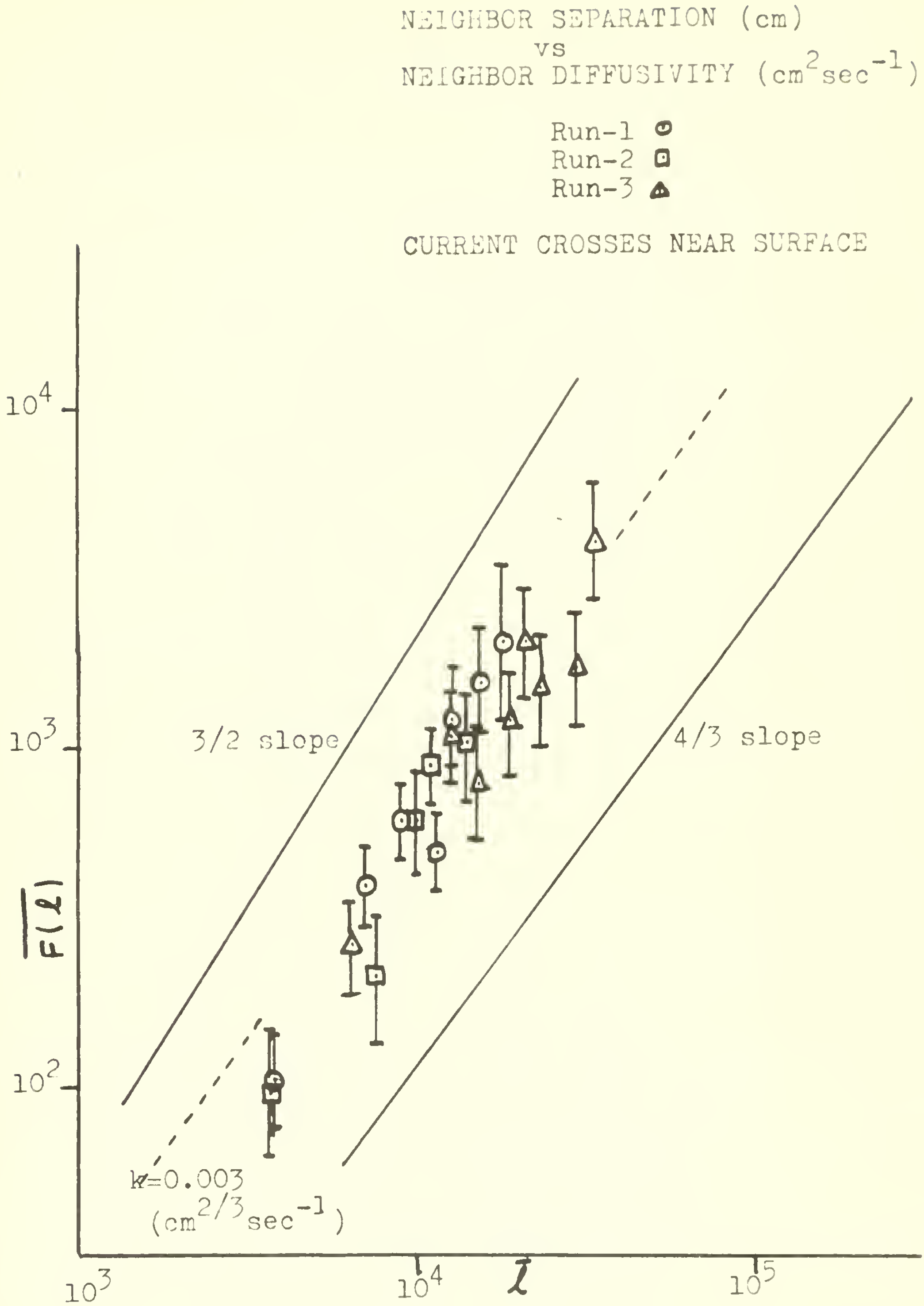
Figure 1 (current crosses near surface)	$K = 0.003 \pm 0.002$
Figure 2 (current crosses at nine feet)	$K = 0.003 \pm 0.002$
Figure 3 (plywood floats without current crosses)	$K = 0.006 \pm 0.002$
Snyder (1967, paper sheets)	$K = 0.006$
Snyder (1967, current crosses at nine feet)	$K = 0.002$
Ozmidov (1957)	$K = 0.008 \pm 0.002$

NOTE: Snyder did not report confidence limits on K.

The values of K do not change appreciably with depth. The weight of the diffusers, however, does effect the value of K by a factor of about two. Snyder's (1967) result using current crosses was lower than any calculated in this study. This may be due to either sampling errors or possibly long term variations in ϵ. Using diffusers without current crosses yielded a value for K that is in agreement with those of both Snyder and Ozmidov (1957).

Eighty-percent confidence limits were calculated for $\overline{F(\ell)}$ using the number of values averaged for each point as the degrees of freedom of a chi-square distribution. This procedure is based on the fact that Stommel's approximate solution of the neighbor diffusion equation shows $(\ell_1 - \ell_0)$ to be normally distributed. While a line of four-thirds slope fits the plotted data points quite well, in all cases a line of steeper slope gives a better fit. For example, the relation $F(\ell) = K \ell^{1.612}$ gives the best-fit line for Figure 3. Snyder, using paper sheets as diffusers, obtained a best-fit relation $F(\ell) = K \ell^{1.492}$ for data obtained in the same area as this experiment.

Roberts (1961) theory of turbulent diffusion, based on Kraichnan's (1959) work, predicts a 3/2 slope. The results all suggest a power law fractionally larger than the one studied, thus offering some experimental confirmation of Robert's theory. However, this is certainly not conclusive, and warrants further investigation. To do this a study of diffusion on widely separated scales would be useful.



NEIGHBOR SEPARATION (cm)
vs
NEIGHBOR DIFFUSIVITY (cm^{2}sec^{-1})
Run-1
Run-2
Run-3
CURRENT CROSSES NEAR SURFACE
10^4
10^3
10^2
3/2 slope
4/3 slope
k=0.003
(cm$^{2/3}$sec^{-1})
$\overline{F(\ell)}$
10^3
10^4
ℓ
10^5

FIGURE 1

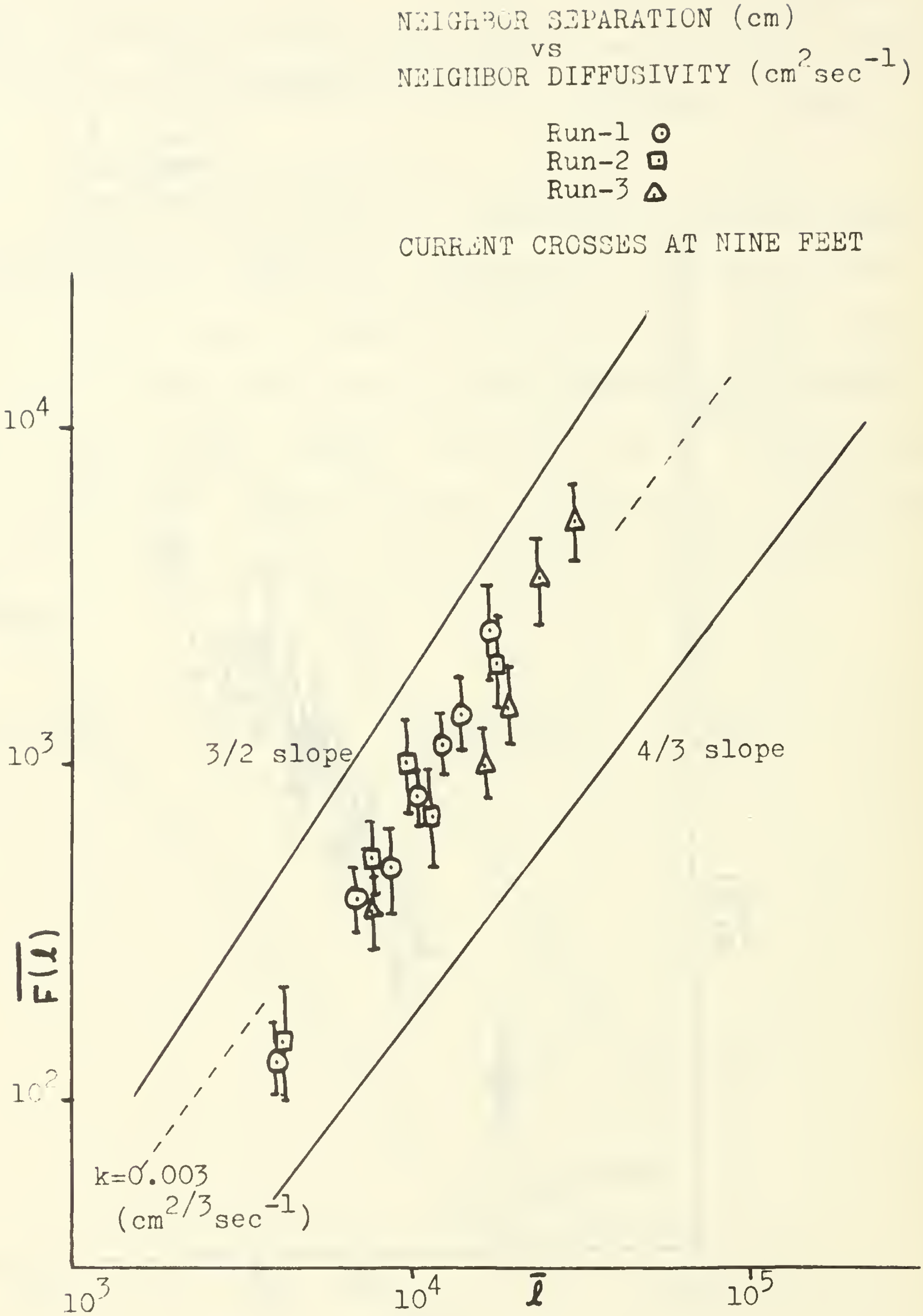

NEIGHBOR SEPARATION (cm)
vs
NEIGHBOR DIFFUSIVITY (cm^{2}sec^{-1})
Run-1
Run-2
Run-3
CURRENT CROSSES AT NINE FEET
10^4
10^3
10^2
3/2 slope
4/3 slope
$\overline{F(\ell)}$
k=0.003
(cm$^{2/3}$sec^{-1})
10^3
10^4
$\bar{\ell}$
10^5

FIGURE 2

NEIGHBOR SEPARATION (cm)
vs
NEIGHBOR DIFFUSIVITY ($cm^2 sec^{-1}$)

Run-4

PLYWOOD FLOATS WITHOUT CURRENT CROSSES

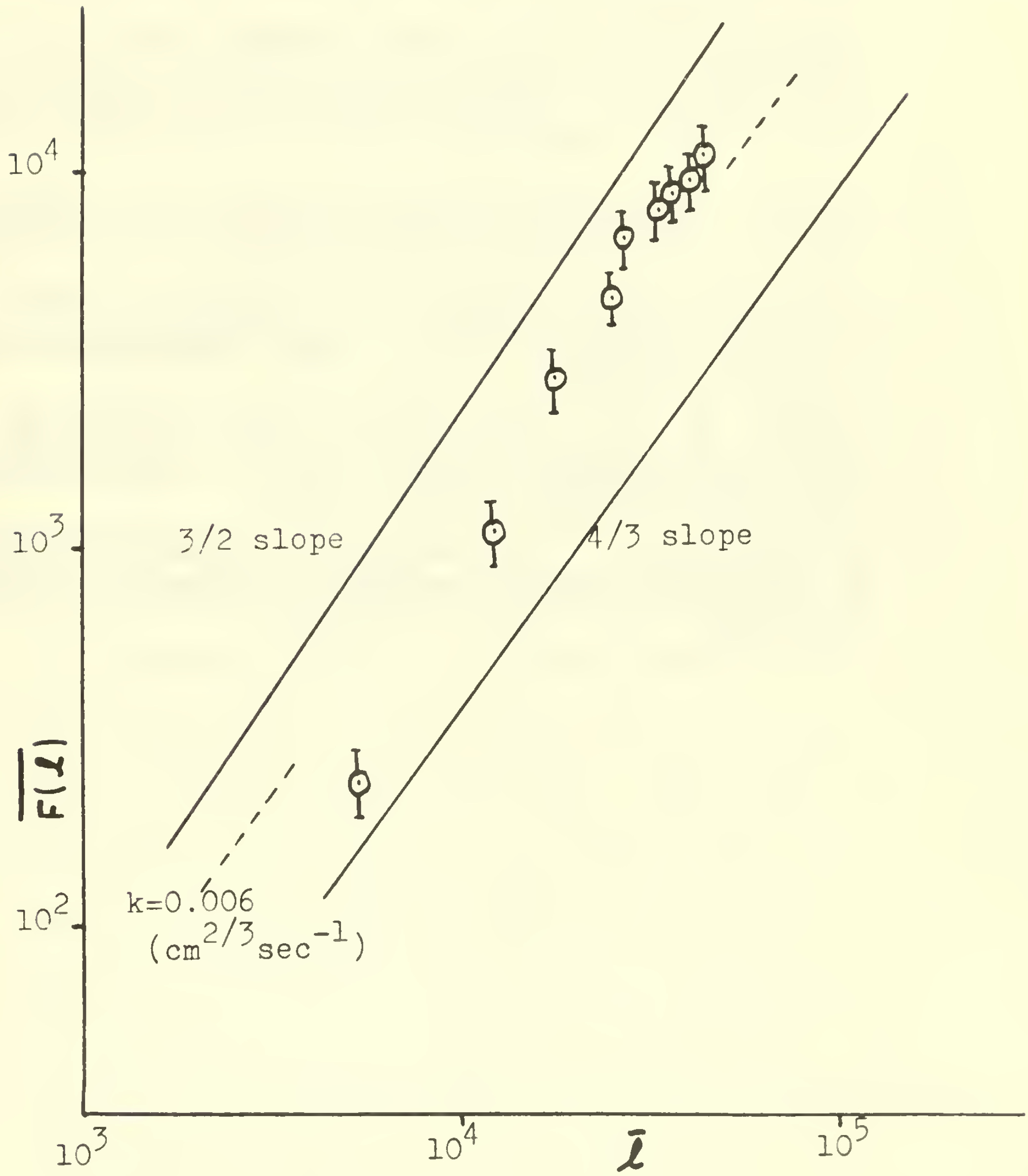


FIGURE 3

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APPENDIX I

Description of Camera Installation

The T-11 aerial mapping camera was installed in a Navy US2-A aircraft just aft of the radome. The radome and associated electronic equipment had been previously removed, so the weight of the camera (110 pounds) did not present a stability and therefore safety problem.

The access door for the radome compartment was removed and an aluminum plate fashioned to the same size as the access door set in its place. The hinge and latch arrangements of the original installation were used to hold the aluminum plate in place. A hole of identical size and shape as the lens housing was cut into the plate to accommodate the camera. Four, twelve-inch steel bolts were fastened perpendicular to the aluminum plate with aircraft self-locking nuts. A steel retaining ring was placed over the steel bolts and held in place by leveling nuts. The plane was then positioned in a level flight attitude by means of hydraulic jacks, and the camera secured to the plate by the retaining ring. The retaining ring leveling nuts were adusted so that the lens axis was set in the vertical. This critical alignment was made with the aid of the liquid level bubbles on the camera housing.

Electrical power came directly off the airplane's main d.c. power supply. The source of the two-inch mercury vacuum was the de-icing system. Circuit breakers, located in the cockpit, were installed to isolate the camera's electrical system as an added safety precaution. The circuit breakers were kept open at all times except when actually engaged in picture taking runs. During these runs the anti-collision light located immediately forward of the camera lens was turned off for obvious reasons.

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13. ABSTRACT

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DIFFUSION						
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